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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

MODELING JAMMING EFFECTS ON ROLLING AIRFRAME MISSILE

by

Chia-Chun Yen

September 2001

Thesis Advisor: D. Curtis Schleher
Second Reader: David C. Jenn

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13. ABSTRACT ***(maximum 200 words)***

Development of countermeasures against infrared and optical guided missiles is enhanced by an ability to quantify the effects of the countermeasure. Analysts must be capable of accurately determining the attitude of the missile throughout its flight. This thesis describes the use of microelectronic-miniature (MEM) technologies to measure the strap down rates experienced by a rolling airframe missile and the model required to effectively determine the missile's attitude during its flight. The Tokin America CG-16D rate sensors and the Honeywell, SSEC, HMC 1002 roll sensor were used in an inertial measurement unit (IMU). The size of the IMU is small and rugged enough to be installed in a small diameter missile. A SIMULINK model is presented that performs the tasks of demodulating the sensors, performing coordinate transformation, and providing animation of the missile attitude for analysis. The model was evaluated for its ability to accurately determine the attitude of the missile based on input from the IMU packages. Sensor data was obtained from testing performed on a CARCO table flight motion simulator, and compared to the ground truth data provided by the CARCO table. Previous research had proved that this model worked for slow- spinning missile (5 Hz in roll). This thesis research expands that research to a fast spinning missile (15 Hz in roll). Through testing, the model was capable of providing solutions within the 2 degrees RMS requirement.

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MODELING AND SIMULATING OF ROLLING AIRFRAME MISSILE

Chia Chun Yen
LCDR Taiwan Navy
B.S., Chinese Naval Academy, Taiwan, class of 1988

Submitted in partial fulfillment of the
requirements for the degree of

**MASTER OF SCIENCE IN
SYSTEMS ENGINEERING**

from the

**NAVAL POSTGRADUATE SCHOOL
September. 2001**

Author: Yen, Chia Chun
Chia Chun Yen

Approved by: D. Curtis Schleher
Curtis D. Schleher, Thesis Advisor

David C. Jenn
David C. Jenn, Second Reader

Dan C Boger
Dan C. Boger, Chairman, Information Warfare Academic Group

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ABSTRACT

Development of countermeasures against infrared and optical guided missiles is enhanced by an ability to quantify the effects of the countermeasure. Analysts must be capable of accurately determining the attitude of the missile throughout its flight. This thesis describes the use of microelectronic-miniature (MEM) technologies to measure the strap down rates experienced by a rolling airframe missile and the model required to effectively determine the missile's attitude during its flight. The Tokin America CG-16D rate sensors and the Honeywell, SSEC, HMC 1002 roll sensor were used in an inertial measurement unit (IMU). The size of the IMU is small and rugged enough to be installed in a small diameter missile. A SIMULINK model is presented that performs the tasks of demodulating the sensors, performing coordinate transformation, and providing animation of the missile attitude for analysis. The model was evaluated for its ability to accurately determine the attitude of the missile based on input from the IMU packages. Sensor data was obtained from testing performed on a CARCO table flight motion simulator, and compared to the ground truth data provided by the CARCO table. Previous research had proved that this model worked for slow- spinning missile (5 Hz in roll). This thesis research expands that research to a fast spinning missile (15 Hz in roll). Through testing, the model was capable of providing solutions within the 2 degrees RMS requirement.

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Finally, I would like to thank God for giving me such a wonderful chance to extent the horizon of knowledge, to pursuit for further education and to appreciate the marvelous work of His creation.

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I. INTRODUCTION

A. BACKGROUND

In the field of anti-air missile system, infrared guidance (IR) has increased the lethality of missile systems worldwide. Combination of radar and infrared-guided system has become a trend of modern missile design. In the period 1979 to 1985, 90% of aircraft lost in combat were destroyed by IR guided missiles (Naval Air Systems Command [NAVAIRSYSCOM], 1988). It had clearly shown that the effectiveness of IR missile had exceeded that of the radar guided missile. However, due to the inability to effectively test and quantify the effects of countermeasures on IR guidance system, the countermeasures developed against this threat have been limited.

In order to develop effective countermeasures of IR missiles, Naval Air Warfare Center (NAWC) China Lake has identified a need for a post-flight computer recreation of missile attitude and position throughout its trajectory. Only then can the effectiveness of countermeasures be properly assessed. Quantifying the effects of countermeasures requires very detailed information about the response of the missile to the countermeasure. The exact position and attitude of the IR missile throughout its flight should be determined to analysis the effects of the countermeasure.

In the test ranges throughout the world, several methods are used to track missiles in flight and determine the time, space, and position information (TSPI) of the missile: 1) high-speed photography, 2) radar tracking, 3) laser tracking, 4) Global Positioning System (GPS) tracking. Each of these methods has its own benefits and deficiencies that prevent any one method from being superior to one another. All methods above are either expensive or provide no attitude information of the tested missile. For the testing of radar

guided missiles, traditional gyro –based inertial measurement units (IMU) were used to re-create the missile's attitude in flight. Due to the space constraint, a gyro –based IMU is not feasible in the case of IR guided missiles. To overcome this obstacle, numerous other micro-miniature technologies have been used with success. In 1999, Prof. Curtis Schleher and Troy Johnson, at the Naval Postgraduate School were able to achieve an accuracy of less than 2 degree RMS with telemetry data from a quartz-rate sensor installed in a non-roll stabilized missile. In 2000, Prof. Curtis Schleher and Craig A. Hill applied the concept with a different IMU package to a roll stabilized missile. However, their research did not explore missiles that spun faster than a rate of 5 Hz. Most of the rolling airframe missiles spin at rate between 15-20 Hz. As the same model was applied for 15Hz rolling rate missile, the error may grow larger and it may be not feasible to re-create the missile's attitude. This thesis expands the work performed by Prof. Curtis Schleher and Craig A. Hill to quantify the effect of rapid spinning rolling missile.

B. APPROACH

Collections of rate information are required to reconstruct missile attitude. A PC based model was introduced to interpret and to simulate the yawing and pitching of the missile. To collect the rate data, an IMU assembly is installed in the missile and the IMU sensor data is transmitted to a ground station where it is collected for analysis. The IMU required for a roll stabilized missile consists of a sensor for sensing roll angle and two angular rate sensors for sensing rates relative to the pitch and yaw axes.

Once collected, the data is introduced into a conditioning model where bias is removed, and scale factors are applied prior to use in the simulation model. Within the

simulation model, the rate sensor data is demodulated using roll angle, providing pitch and yaw rates in the missiles frame reference, or strap-down. Cross coupling is then corrected. Once complete, then earth reference is applied through coordinate transformation. In coordination transformation the attitude of the missile in pitch and yaw is determined based on the relation of the missile's rates, R,Q, and P, to the earth using the Euler rotation model. Once transformed, the pitch and yaw angles are used to provide a visual display of the missile attitude throughout its flight.

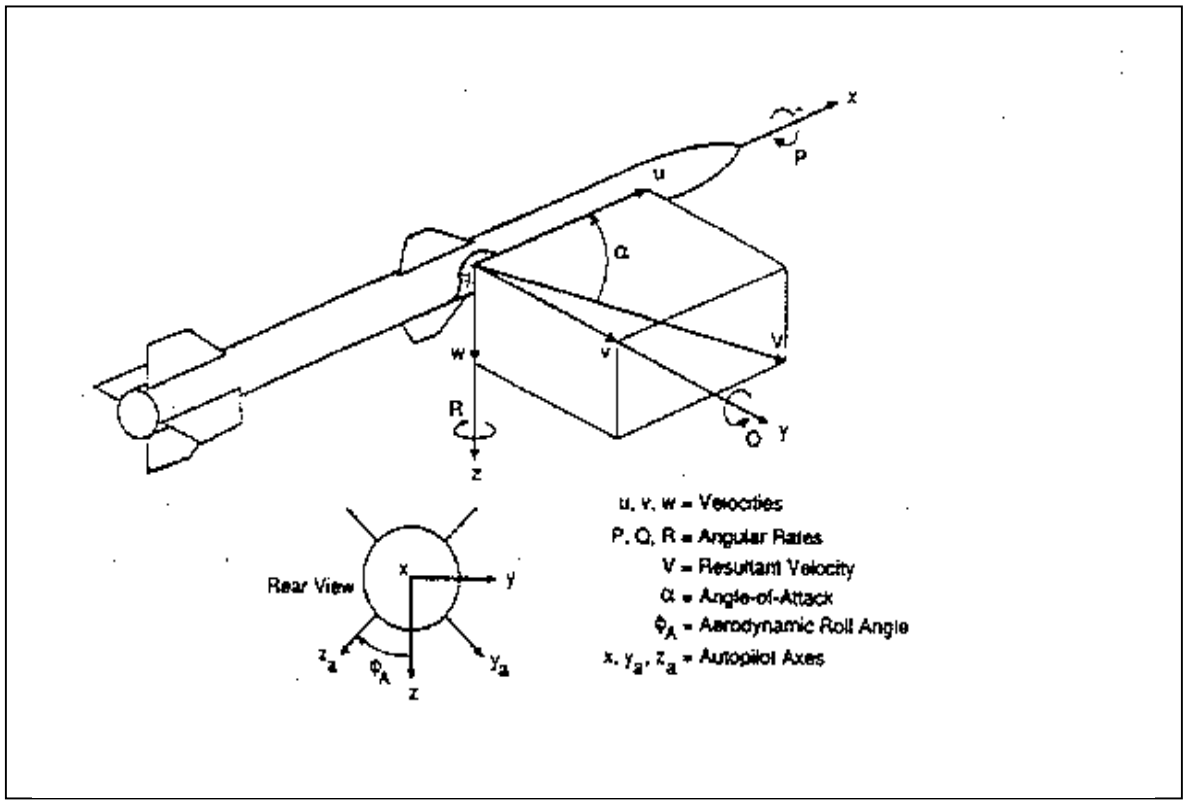

Figure 1. Missile Attitude

The Euler rotation model operates on the convention of the aerospace industry. As shown in Figure 1, the attack angle (α) is the angle between the resultant velocity vector (v) and the x-axis of the missile. Missile's attitude is defined by the pitch (θ), yaw (Ψ), and roll (ϕ) angles of the missile. Pitch is defined as the angle between the central line, x-

axis, of the missile, and the velocity component in the x-z plane. Yaw is defined as the angle between the central, x-axis, of the missile and the velocity component in the x-y plane. Roll is defined as the angle between the central, x-axis, of the missile and the velocity component in the y-z plane. The rates experienced relative to these axes are defined as Q about the pitch axis, R about the yaw axis, and P about the roll axis. These six components described above completely define the attitude of the missile in flight.

The combination of rate sensors and roll sensor compose the IMU package. The IMU package was tested using a flight motion simulator and the data relayed from the sensors during the tests were evaluated for effectiveness and accuracy, and compatibility with the Euler rotation model.

C. QUESTION ANSWERED

Several questions were answered in the conduct of this research:

1) Can the attitude profile of an rolling airframe missile (RAM) be successfully modeled within a specified level of accuracy of 2° by using a miniature missile-mounted telemetry package?

2) Are SIMULINK numerical solver procedures capable of providing the required precision to accomplish the task listed in the first questions?

3) Do the "rate gyro" sensors possess the requisite stability, dynamic range, and precision to accomplish the task set forth in the primary research question?

The methods and quantitative results of this research are presented in the pages below. Briefly, the answers to these questions are presented here:

1) Yes, the attitude of a rolling airframe missile can be determined with a high degree of accuracy using this IMU package and a computer simulation model as long as the rate and rolling sensors provide accurate data. 2)

2) Yes, the SIMULINK numerical solver procedures are capable of providing the required precision. 3) Yes and no, the rate sensors do possess the required stability, dynamic range and precision to accomplish the telemetry task but the roll sensor in its present location was proven not stable enough to provide correct roll angle reference.

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II. SENSOR DESCRIPTION

The IMU for the rolling missile is composed of three principal components, two Tokin America CG-16D rate sensors to sense pitch and yaw and one Honeywell HMC1002 Dual –axis Discrete Magnetic Sensor to sense roll. The rate sensors are installed orthogonal to one another parallel to their respective axis.

The three components necessary to describe the attitude of the missile are provided by the IMU package. Pitch and yaw rate sensors are necessary to solve for the pitch and yaw angles. Roll position is necessary to provide the phase information required for demodulation of the pitch and yaw rates.

A. ROLL SENSOR

The roll sensor used was the HMC1002 Dual –axis Discrete Magnetic Sensor designed and built by Honeywell. The HMC1002 is a micro-miniature, low field, solid state sensor capable of measuring direction and magnitude of a magnetic field of ± 2 Gauss. It is small and rugged enough to be installed in the IMU package, and is capable of sensing the earth's magnetic field. Table 1 shows the specification of this roll sensor.

The Honeywell HMC1002 operates on the principle of anisotropic magnectoresistance (AMR). AMR causes a change in a ferrous material when a magnetic field is applied across the material. The magnitude of the resistance changes with the angle of incidence of the magnetic field on the conductor. When parallel to the flow of current, the added resistance is zero. When orthogonal to the flow of current, the added resistance is at its peak. These changes in resistance, depicted in the output of the sensor,

are highly predictable and can be used to determine the angle of incidence of the ambient magnetic field.

Characteristic	Conditions	Min.	Type	Max.	Unit
Power supply	V bridge referenced to GND		5	12	Volts
Bridge resistance	Bridge current=10mA	600	850	1200	Ohm
Operating Temp.		-40		125	C
Field range	Full scale, total applied field	-2		+2	Gauss
Resolution	At Bandwidh=10Hz, Vbridge=5V		27		μgauss
Bandwidth	Magnatic signal(low limit=DC)		5		MHz
Linearity range	Beat fit straight line +/- 1 gauss +/- 2 gauss		 0.1 1	 0.5 2	%Full scale
Weight			0.53		Gram

Table 1. HMC1002 roll sensor specifications (From: Honeywell SSEC, 2001 Data sheet)

The HMC1002 should be mounted along the x or central axis of the missile. However, for the IMU tested in this thesis research, the HMC1002 sensor was mounted 0.65 inch off the central axis and was 58 degrees off the yaw axis. As the missile rotates, the output voltage reaches its greatest positive magnitude as the magnetic flux on face of the MR strip reaches its maximum. As the missile rolls 90 degree and the MR strip becomes parallel to the flux of the magnetic field, the added resistance is zero. When the missile rolls another 90 degrees, the added resistance is again at its maximum but inverted to give a negative voltage. As the missile rolls through 360 degree, the sensor output describes a sinusoidal wave that reflects the roll position of the missile (ϕ).

B. RATE SENSORS

Like the roll sensor, the rate sensors should be small enough to fit into the IMU package and exhibit the same performance in accuracy and reliability. The rate sensors are vital to accurate modeling of the missile's attitude. It measures the rates, Q and R, experienced by the missile by its pitch and yaw axes.

By definition, the pitch and yaw axes should be orthogonal to each other. Referring back to Figure 1, Pitch is the angle between the central line, x-axis, of the missile, and the velocity component in the x-z plane. Yaw is the angle between the central, x-axis, of the missile and the velocity component in the x-y plane. In order for the sensors to accurately read the yaw or pitch rates, they must be perfectly aligned in their respective planes. Any deviation from alignment will cause excessive influence of rates along one axis on the rate sensor aligned to the other axis. The sensor with high cross axis sensitivity will be affected by rates that are not along its sensitive axis and will therefore provide incorrect output. In order to avoid this situation, sensors must be orthogonal with resulting low cross axis sensitivity.

The rate sensor used in the IMU package was the Tokin America CG-16D. Designed for application in vehicle navigation system and as a hand held camera image stabilizer, the Tokin sensors met the size requirements at 8x20x8 millimeters. A complete set of specification is presented in Table 2.

A ceramic gyro, the Tokin sensor has a very basic construction of a ceramic column printed with electrodes and operates on the principle of the piezoelectric effect. In short, the piezoelectric effect occurs when an ionic bounded crystal is placed under stress. When stress is applied, the crystal deforms and a dipole moment is created. This dipole moment creates an electric field that, in turn, generates a charge that is proportional to the pressure applied. In the presence of reciprocating pressures or rates as experienced by a rolling missile, an alternating current is produced. This current reflects the rates that the sensor experiences about the pitch or yaw axis.

Characteristic	Conditions	Specifications	Unit
Supply voltage		+5	V
Current consumption	Max.	7	mA
Reference voltage output		+2.4	V
Maximum detectable angular rate	25°C	±90	deg/sec.
Sensitivity	25°C	1.1±20%	mV/deg/sec
Output voltage at zero angular rate	25°C	±300	mV
	Any temp.	±600	mV
Temp. characteristics of sensitivity		±15	%
Frequency response	Min. 90deg	100	Hz
Operating temperature range		-5~75	°C
Storage temperature range		-40~80	°C
Characteristic	Conditions	Specifications	Unit
Dimensions		8x20x8	mm

Table 2. Tokin Rate sensor specifications (From: Tokin Inc. CG-16 Data sheet)

III. TELEMETRY PACKAGE DESCRIPTION

The method of sensing the inertial rates in the missile's frame of reference and reporting them back to a fixed station, was highly effective due to the IMU's compact size, use of low cost sensors, and ability to thoroughly validate the model. Earth-referenced angles were produced with exceptional accuracy without the expense and complexity of gyro-based systems.

Critical performance data is gathered by mounting a telemetry system and IMU sensors within the body of the missile where the warhead would normally reside. The telemetry system transmits a high frequency carrier that is modulated with output signals taken from rate sensors contained in the IMU. In this particular case, the telemetry data provides 12-bit accuracy at a 1389 Hz sampling rate. The sensor indications are transmitted to a base station where they are stored for future analysis. The rate data is used as the input to a PC-based model constructed using MATLAB and SIMULINK computer software to convert the strap-down yaw, pitch and roll rates (R, Q, and P) to Euler angles (ψ,θ, and ϕ) in the earth references.

The reconstruction of the rolling missile attitude in flight needs precise information from different sensors at the same time. The telemetry package is composed of the IMU, modulator, transmitter, receiver, conditioner, and demodulator model. It had been proven to be efficient and reliable in accordance to previous reliability test research done by the China Lake test range.

The use of motion platforms to simulate missile test flights saves a lot of money in development of modern missiles. The flight motion simulator must be capable of exercising the test unit in at least three independent axes to simulate the flight attitude. In

this thesis research, data collection was performed using a flight motion simulator manufactured by CARCO Electronics Inc. The CARCO table is an electro-hydraulically operated table capable of exciting an installed object in five axes simultaneously. It is also capable of outputting its exact alignment measured in angular position throughout the test, providing ground truth against which model effectiveness can be measured. The CARCO table is shown in Figure 2. For testing purposes, the fourth and fifth axes were not used and have been removed from the figure.

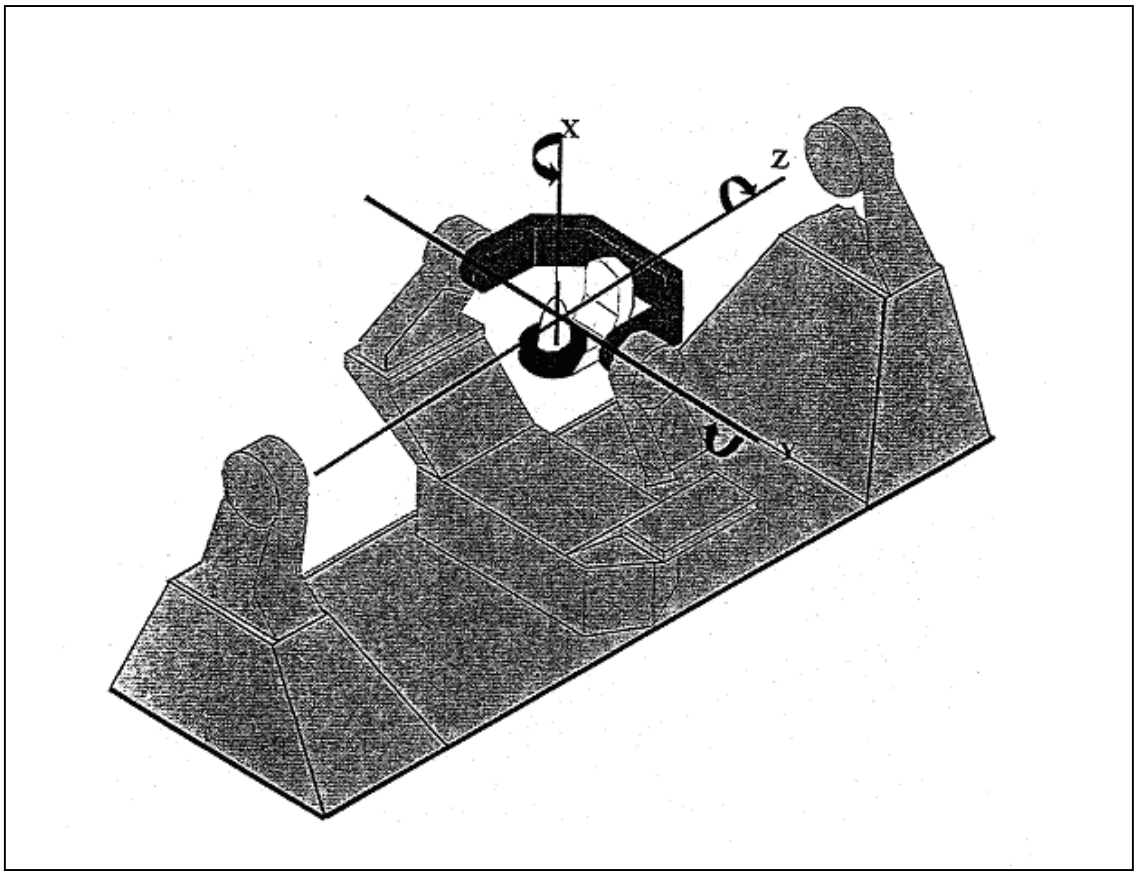

Figure 2. CARCO Table with Fourth and Fifth Degree of Freedom Gimbals Removed

IV. MODEL FUNCTION DESCRIPTION

A. ENVIRONMENT

Modeling of the rolling airframe missile in this thesis research was performed using SIMULINK 6.0 produced by the Math Works Inc. MATLAB is a language specifically optimized for use in matrix and vector calculations. SIMULINK extends the functionality of MATLAB by providing a user friendly, point and click interface to perform modeling and simulation of different works. Using the ordinary differential equation solvers of MATLAB language, SIMULINK provides near real time solutions to simulations and models and can access all the functionality of the MATLAB language.

Data collection is performed on site at the China Lake missile range. IMU sensor data is transmitted from the missile and is processed to 12-bit accuracy at a sampling rate of 1389 Hz. Once collected, the data is converted to ASCII format in columnar tables. Because of the input data format requirement of SIMULINK, several changes are made to the files. First, SIMULINK operates only on MATLAB binary files that are in the form of matrices in which time is located in the first row. Conversion requires the removal of header data from the ASCII file. Then, the file must be opened in the MATLAB environment, transposed and saved as a MATLAB binary file. Additionally, time must be changed from range time to a zero origin time with step sizes of 1/1389. When all these changes stated above have been completed, the data is ready for introduction in the SIMULINK environment.

B. FUNCTIONAL DESCRIPTION

The model performs four principal operations, 1) conditioning, 2) demodulation, 3) coordinate transformation, and 4) animation. All these operations are performed in the

SIMULINK environment using the SIMULINK and MATLAB functions. The functional diagram is shown as Figure 3.

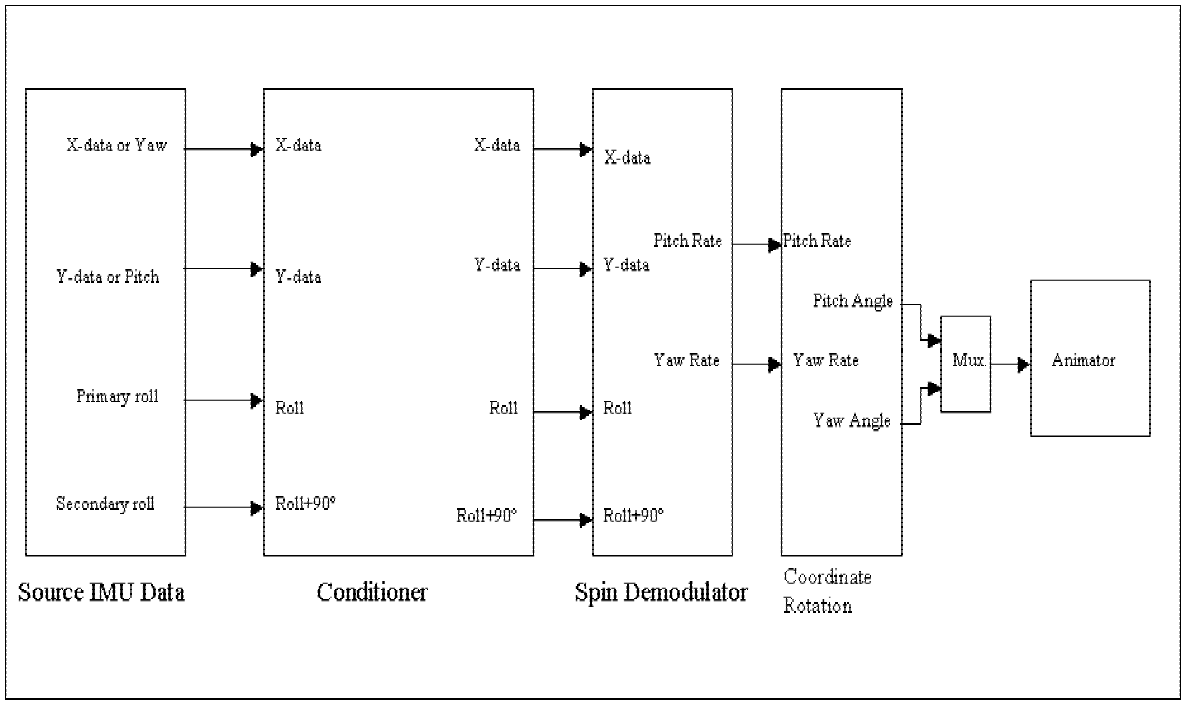

Figure 3. Model Functional Diagram

1.Conditioning

Conditioning is performed on the data to account for inaccuracies in bias, and scale introduced by the sensors. Figure 4 shows the functional flow of the conditioner. The conditioners used for testing are presented in Appendix B. Conditioning is performed as the first step to reduce the mitigation of error throughout the model. Because integration is used for coordinate transformation, any error left uncorrected is compounded throughout the time period of the simulation, leading to significant errors in the final result.

Bias is a product of each individual sensor. When there is no rate experienced on the sensor, there will be as DC value output from the sensor. Bias is typically constant

through time. It is determined by averaging the value of the sample over time. Adding or subtracting a constant to each sample to offset the average to zero can remove the resulting DC value, the bias.

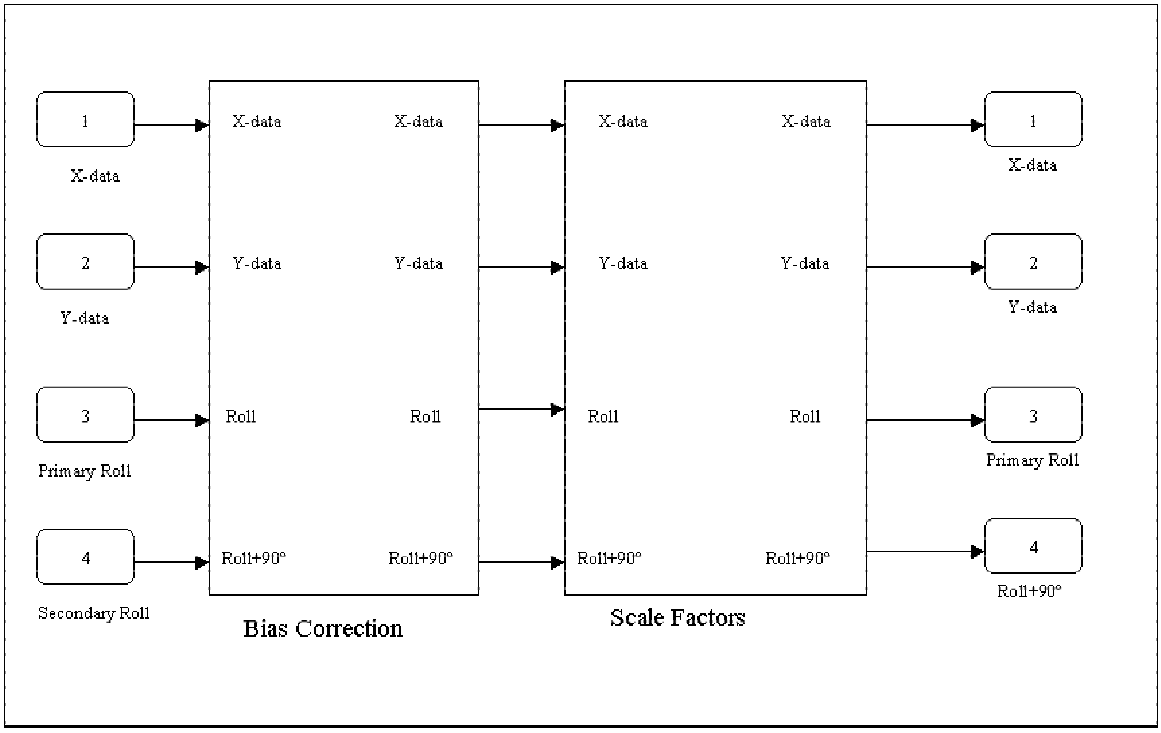

Figure 4. Conditioner Functional Diagram

Scaling errors are errors of magnitude indicated by the sensor. The TOKIN rate sensors output a voltage proportional to the rate that the sensor is experiencing. The magnitude of this voltage must be scaled to accurately indicate the rate being experienced. This scale factor is typically provided by the manufacturer but can be determined through hardware- in- the-loop tests. These tests must be performed in a controlled environment such as a flight motion simulator where rates are known. This approach is impossible in live fire applications due to the unknown rates experienced by the missile. To correct this, each sample of the data is multiplied by the inverse of the scale factor.

Failure to account for and correct either of these errors will reduce the accuracy of the data input to the model. This is in turn will prevent accurate solution of the missile's attitude.

2.Demodulation

The next operation performed by the model is demodulation of the yaw, X-rate, sensor and pitch, Y-rate, sensor data. Because of the rolling action of the missile, demodulation requires a phase reference provided by the roll sensor installed in the missile. The functional diagram of the demodulator is presented in Figure 5.

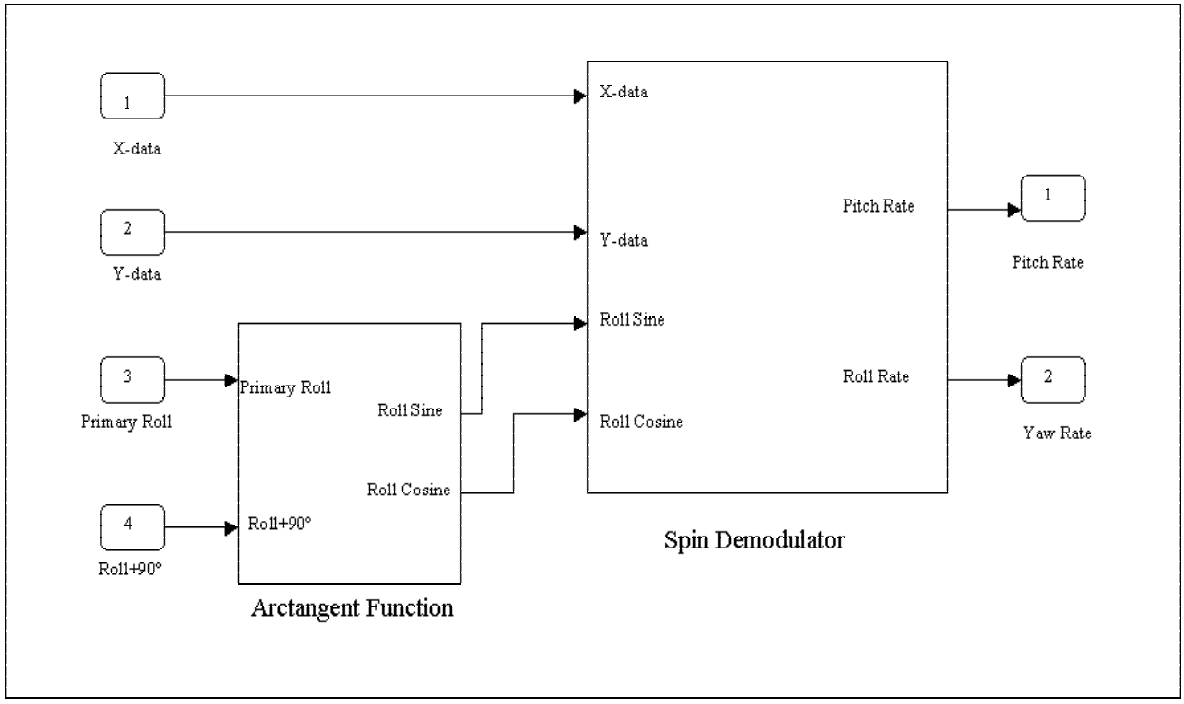

Figure 5. Demodulator Functional Diagram

Because the roll sensor may not necessarily provide a purely sinusoidal wave, the roll sensor output could be conditioned by one of two methods: a phase locked loop or an arctangent function. The arctangent function approach was used in this thesis research.

The phase lock loop uses a voltage–controlled oscillator (VCO) to output a sinusoidal wave matched to the frequency of the roll sensor. The VCO must be tuned to the estimated frequency of the missile's roll and its gains must be adjusted to allow the VCO to accurately track and adjust to any change in the missile's roll frequency.

The arctangent function takes advantage of the dual axis output of the Honeywell HMC1002 sensor. In this method, a four quadrant inverse tangent is taken using the two roll sensor outputs. The output of the SIMULINK "arctan2 " function is then split and run through the "sine" and "cosine" functions of MATLAB. The output of the sine function now matches the output of the roll sensor. However, because it is a function of the dual axis outputs, any common perturbations experienced by the roll sensor can be eliminated.

With a clean roll reference, demodulation is performed from the X and Y rate sensor data. Once the rates along the pitch and yaw axes are known, they must be corrected for cross coupling.

Cross coupling is the sensation of a sensor outside its sensitive axis. Most commonly, cross coupling is caused by a failure to ensure that the sensors are installed orthogonal to one another. This is best represented by placing an angular rate immediately along the axis of one of two "orthogonal" sensors. This rate should only be sensed in the sensor whose sensitive axis lies along the direction of that rate. If the second sensor is not perfectly orthogonal, then that sensor will sense a small portion of the rate. The result will be an addition to that sensor's output beyond what it is sensing along its own intended axis of sensitivity. The cross coupling can be identified by observing excitations about a single axis. When this is accomplished for single axis excitation about both axes, a clear determination is made for the amount of cross

coupling. In the absence of single axis excitation on both axis, the cross coupling can be determined through trial and error. With the amount of cross coupling identified, it can be removed by adding or subtracting an appropriate portion of the opposing sensor's output.

3.Strap-down to Earth Reference

Once demodulation is complete, the resulting rates are introduced into the Euler rotation model for coordinate transformation from strap-down to earth reference. This transform effectively takes the rates experienced by the sensor that are relative to the missile coordinate system, or strap-down, and applies them to an earth based reference system. In this manner, the missile's attitude with respect to the earth is determined.

4.Animation

Animation is performed using a modified version of the SIMQUAT demonstration provided in the SIMULINK environment. The SIMQUAT demonstration allows a user to specify angles or angular rate either for Quaternion or Euler rotation visual display. The functionality for the Euler rotation is provided by the MATLAB s-file, EULERROTDISPLAY. This function uses the input Euler angles and sends them to the display where an aerodynamic structure created using MATLAB "patch" graphics is rotated accordingly.

V. MODEL VALIDATION

The model was initially altered to incorporate "ground truth" from the flight motion simulator, CARCO table. This change allowed mathematical comparison between the two sets of data while not changing the functionality of the original model. The resulting functional diagram is presented as Figure 6.

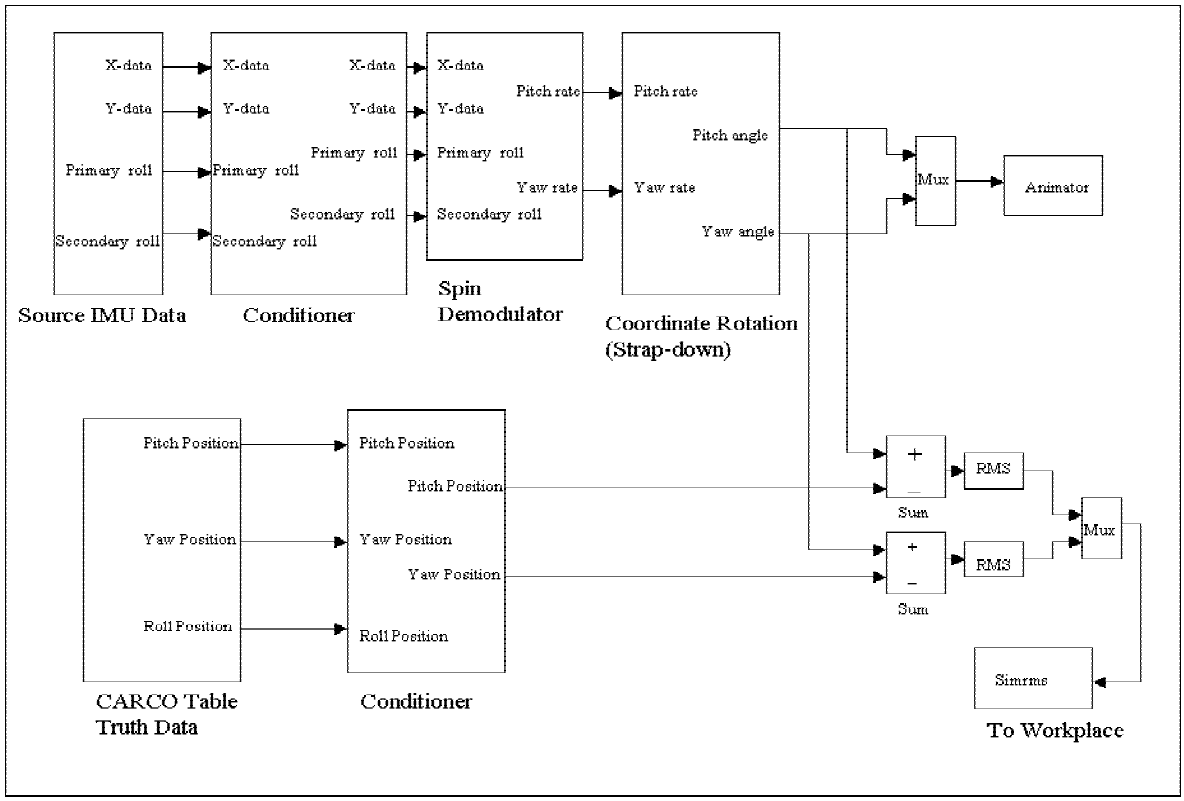

Figure 6. Model Validated with CARCO Table Functional Diagram

When incorporated into the model, the CARCO table data is conditioned similarly to the sensor data in order to remove bias, apply scale factors, match CARCO table conventions to industry conventions, and apply delays. Matching conventions could be tedious but necessary because the conventions of the CARCO table do not match the industry conventions. Therefore, what sensors report as positive yaw may be referred to

as negative yaw by the table, despite that the fact that both move in the same direction. In this case, the CARCO table pitch position output was reversed in polarity.

Comparison of the CARCO table truth data and model solution is performed by taking the arithmetic difference between the model solution and the "ground truth" data, and then, determining the RMS difference between the elements. The RMS difference is output to the workspace as a value indicating the difference in degrees which is used to quantify the accuracy of the model's representation of the missile's attitude.

VI. DATA ANALYSIS AND RESULTS

A. ANALYZING APPROACH

In this thesis research, unfortunately, only limited sets of data from two different IMU units, SB020 and RB020, were collected and analyzed. Different sets of test data collected from these two units are listed in Table 3.

Units / Combinations	RB020				SB020					
Pitch ±25°			*	*	*	*			*	*
Yaw ±40°	*	*	*	*			*	*	*	*
Excitation rate 10 deg/sec		*		*						
Excitation rate 20 deg/sec	*				*		*		*	
Excitation rate 40 deg/sec			*			*		*		*
Number of test data collected: RB020 unit: 4 SB020 unit: 6										

Table 3. Collected test data and the combinations of excitations

The rate sensors and roll sensors used in both IMUs are of the same type but different units. The test data are composed of sensor information along with CARCO table information. All data are conditioned and demodulated according to the method mentioned in the model functional description. The conditioner SIMULINK model is presented in Figure 7.

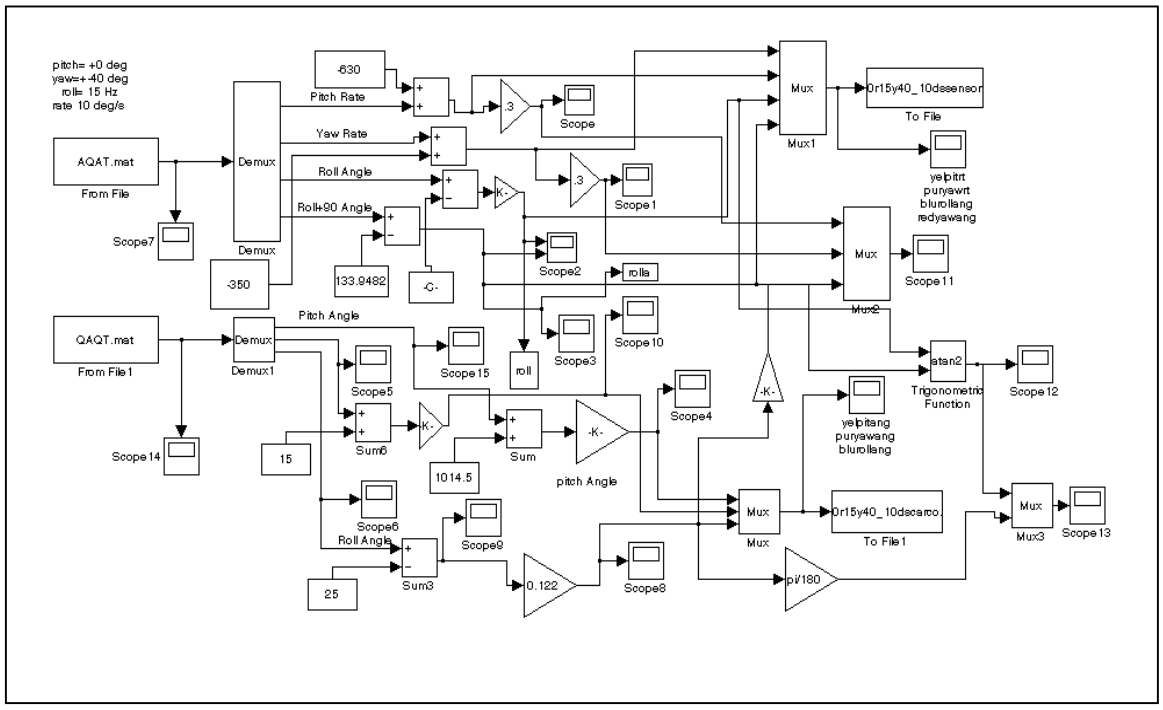

Figure 7. SIMULINK Model- Conditioner

Both RB020 and SB020 were tested on the CARCO table to simulate different attitude of rolling missile that spins at a 15Hz rate. At first the CARCO table roll references were used to demodulate the sensor rate data to find the cross coupling effects and time delay needed for either sensor pitch/yaw rate or sensor roll references for perfect demodulation. Then sensor's roll references were used to perform the same task. The model with CARCO roll reference connected is presented in Figure 8. The model using sensor roll reference is presented in Figure 9. Test data acquired from both units were processed using the same conditioner and demodulation model.

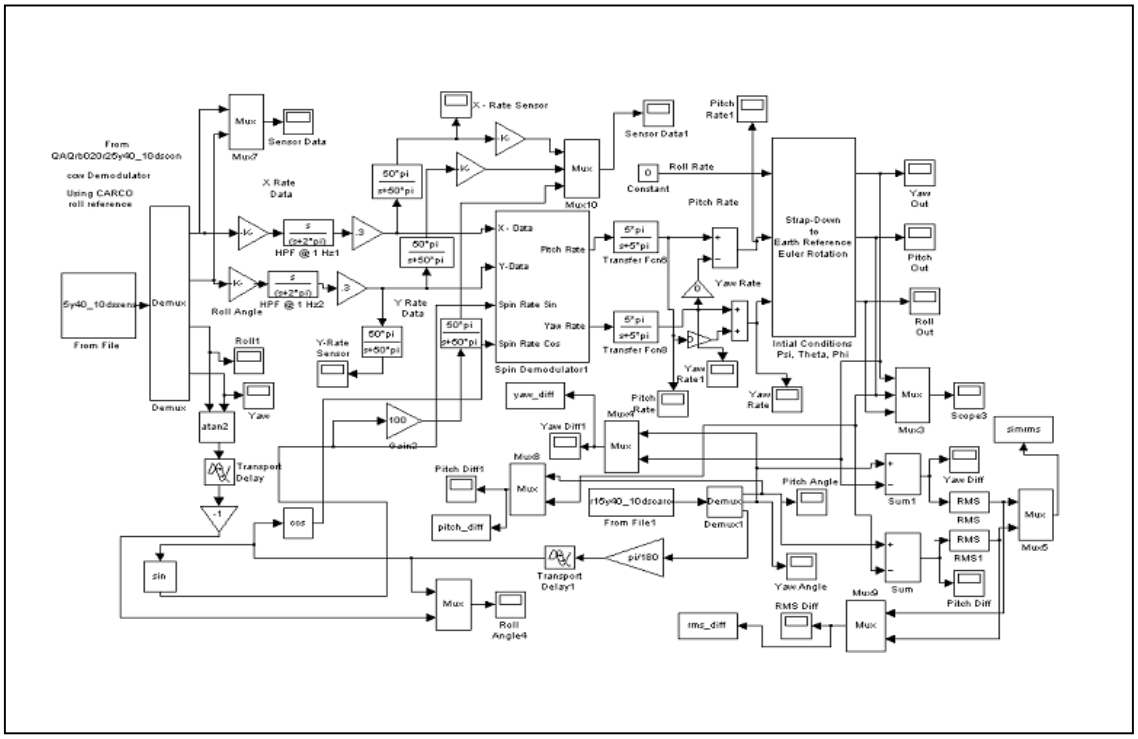

Figure 8. SIMULINK Model- Demodulating Using CARCO Roll Reference.

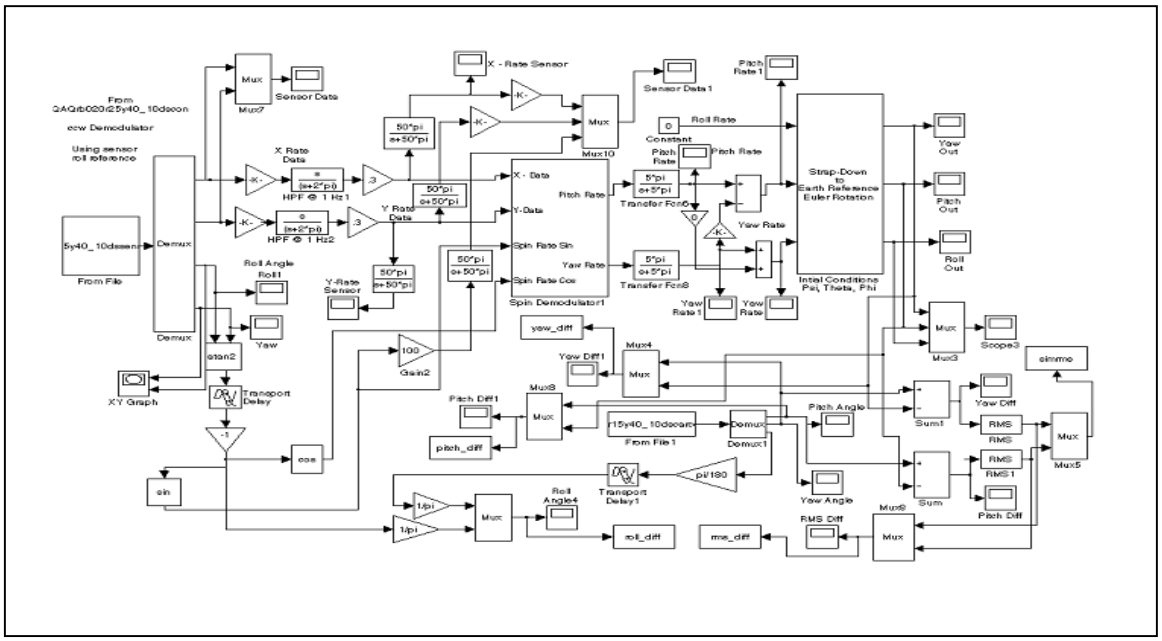

Figure 9. SIMULINK Model- Demodulating with Sensor Roll Reference Used.

B. RESULTS

From the test results for both sensors, it was noted that all the bias and scale factors in the conditioner stays the same for each unit. This indicates that the mechanism of data collecting is stable.

1.SB020 test unit

In the SB020 unit, it was noted from the conditioner that the Roll+90° angle output from the Honeywell HMC1002 roll sensor was distorted. This bad "Roll+90°" signal as processed by the arctangent function failed to produce a roll referenced output that had chain effects on the demodulation process. By comparing the same distorted signal with the signal that was observed from previous thesis research, it was found that it was an isolated problem, which occurred only on the SB020 IMU unit. The comparison between distorted Roll+90°angle signals and roll angle signals are presented in Figure 10.

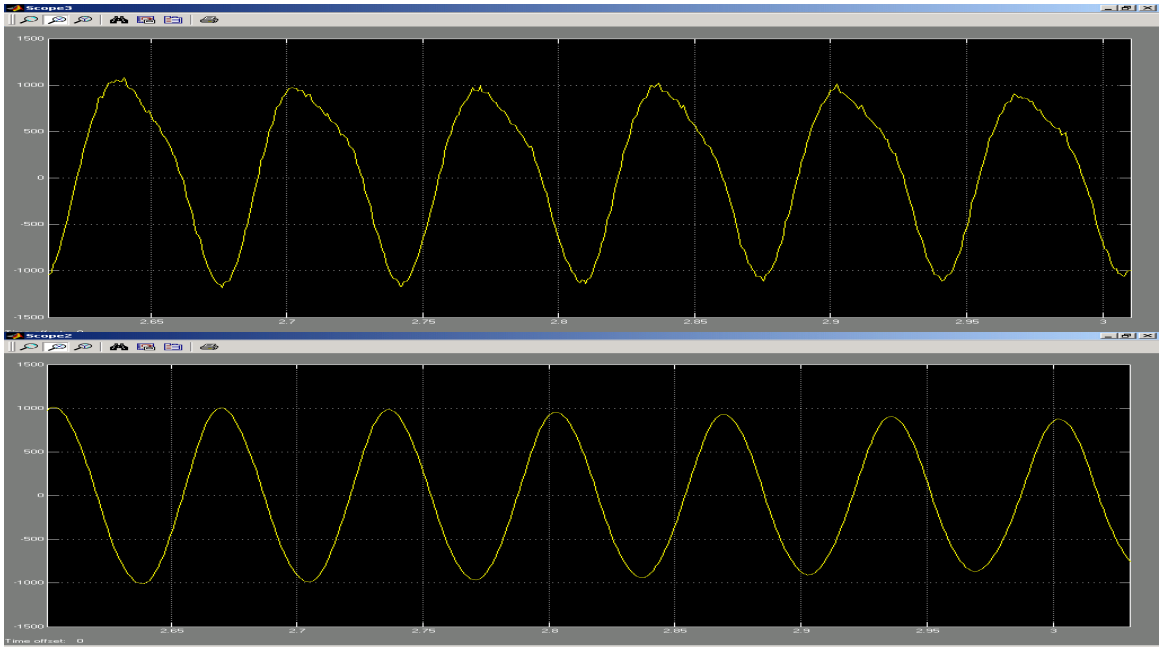

Figure 10. Comparison of Distorted HMC1002 Roll Signal (upper) with Normal Roll Signal (Lower)

In the process of demodulating missile attitude from SB020, when the CARCO table roll signals were used for the spin demodulation, the mean difference values are smaller when the sensor roll reference was used. However, in the case of both pitch and yaw the result was not satisfied. The comparison of Yaw and Pitch difference in different runs is stated in Table 4.

SB020 unit tests analyzed using CARCO roll reference	Mean RMS difference		Cross coupling factor	
	Yaw	Pitch	Pitch to Yaw	Yaw to Pitch
Pitch 25°, 20deg/sec rate	1.4698	1.0295	0	0
Pitch 25°, 40deg/sec rate	0.5313	1.2568	0	0
Yaw 40°, 20 deg/sec rate	0.8841	0.4116	0	0.5
Yaw 40°, 40deg/sec rate	1.7179	0.7349	0	0.5
Yaw 40°, Pitch 25°, 20deg/sec rate	1.6770	2.2929	0.05	0.05
Yaw 40°, Pitch 25°, 40deg/sec rate	0.7708	3.3897	0.1	0.1

Table 4. SB020 unit test results using CARCO table roll reference

In this table, CARCO table roll signals were used as inputs to the spin demodulator. When using sensor roll signal as roll references, 90 degrees phase shifted roll angle data can be used to substitute for the distorted yaw angle data. This is possible since the Roll+90° angle data are from the same type of roll sensor but is mounted 90 degrees apart from the primary sensor. In this particular case, since the Roll+90° signal from HMC1002 roll sensor is distorted, it will be useless to use sensor roll references for further demodulations. In the table above, although the mean RMS difference of pitch only and yaw only runs could be minimized to under 2 degrees, large amount of cross coupling must be used in the demodulator to match the output with the CARCO attitude.

This indicates that the Tokin rate sensors of SB020 may not be perfectly orthogonal to each other.

2.RB020 test unit

For the RB0202 test unit, only 4 sets of test data were provided. In this unit, Roll+90° angle data from Honeywell HMC1002 roll sensor was not distorted like SB020. However, in the demodulation model, the roll angle obtained from sensor arctangent function did not match with those from the CARCO table. The miss-match was not constant throughout the flight. This means that with the constant spinning rate of 15 Hz from CARCO table, the sensed spinning rate from IMU drifted around 15 Hz. Unfortunately, this drift in frequency was not constant so it could not be corrected by simply applying a constant time delay.

The roll reference of demodulation model in this thesis research was made by processing roll and Roll+90° angle through a MATLAB arctangent function, the requirements of this function are that those two inputs must have the same amplitude and the same phase relationship (90 degrees apart). In this unit, the arctangent function could not produce accurate and stable roll angle for the spin demodulator.

Efforts were tried to select a portion of test period in which the sensor roll matched the CARCO roll. For the test run of Yaw 40° and a rate of 10 deg/sec, it was noted that in case of matched roll signals, the demodulated output met the requirement. The mean RMS differences were 0.8308 and 1.1486 degrees for yaw and pitch. The yaw and pitch angle of this test is presented in Figures 11 and 12. The X axes are in seconds, the Y axes are in degrees.

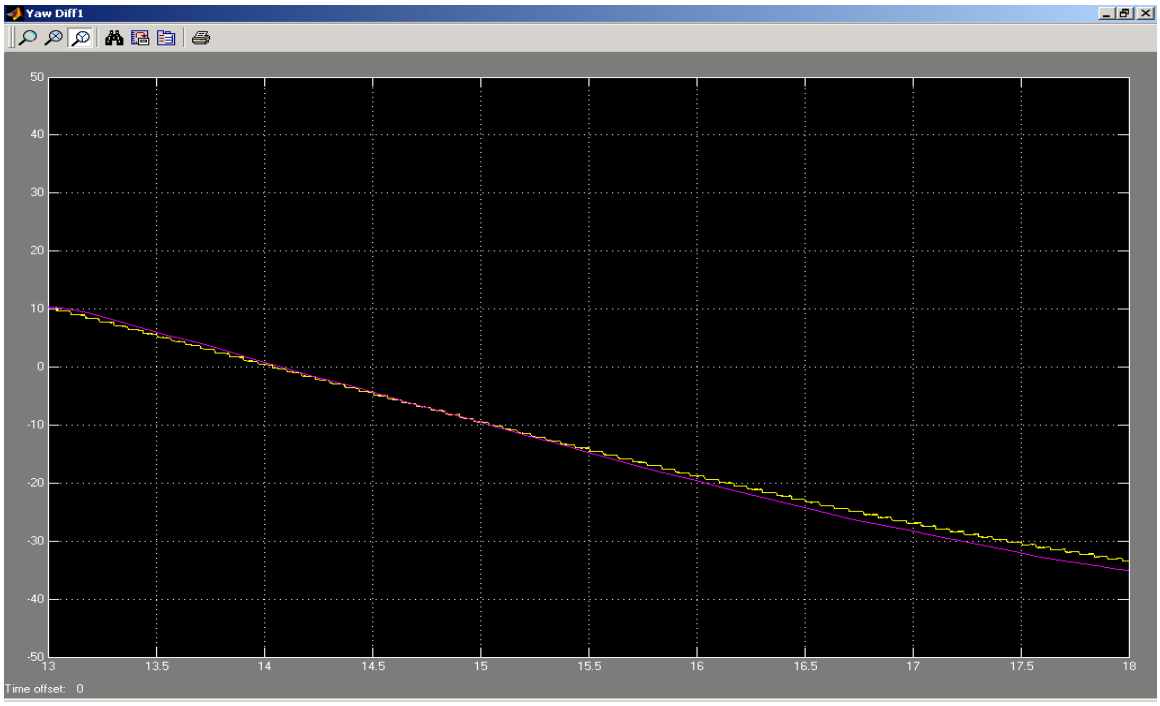

Figure 11. Yaw Angle Difference between Sensor (pink) and CARCO Table (yellow)

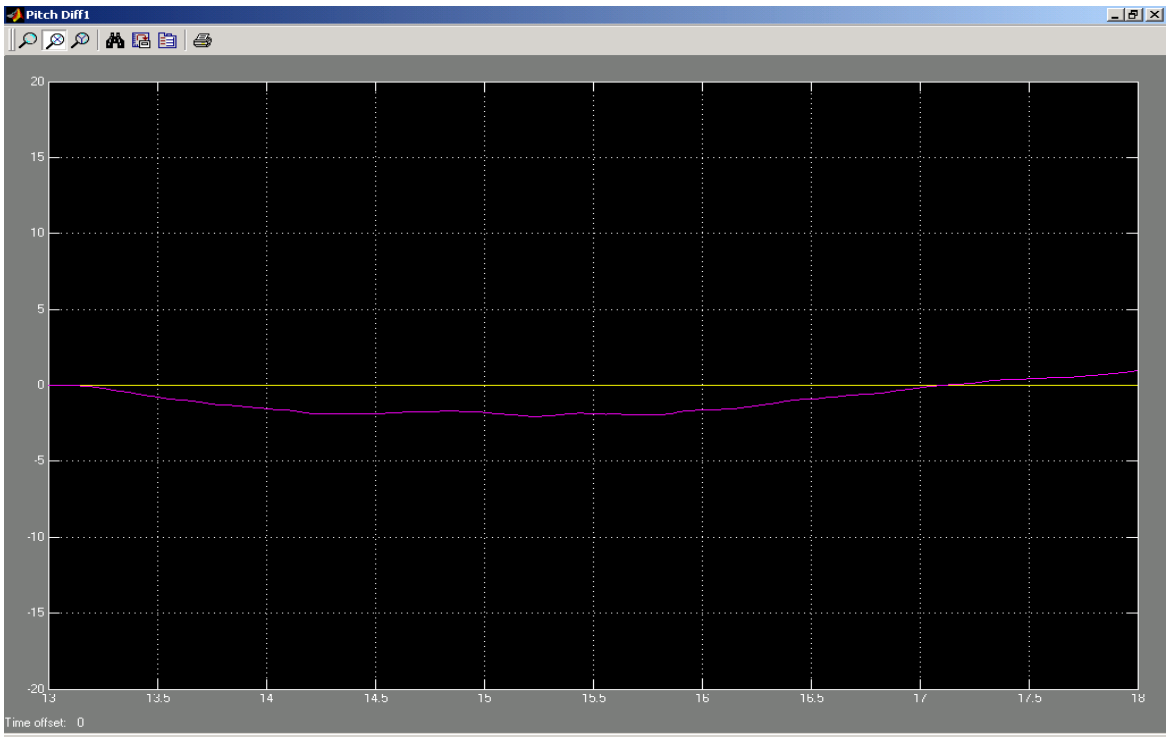

Figure 12. Pitch Angle Difference between Sensor (pink) and CARCO Table (yellow)

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VII. CONCLUSIONS AND AREAS FOR FURTHER RESEARCH

A. CONCLUSIONS

When compared to the missile attitude information from the CARCO table, the IMU data from these two units are not good enough to re-create missile roll. However, as long as the roll reference matches with those from the CARCO table, the demodulated output can be very accurate. When the sensor roll matches the CARCO roll, the RMS value of difference is measured as under 2 degrees for both pitch and yaw. This proves that the numerical method of MATLAB and SIMULINK for modeling and reconstructing missile attitude is feasible.

B. AREAS FOR FURTHER RESEARCH

Reconstructing rolling airframe missile attitude is important for the analysis of countermeasure effects. The compact sized IMU and the numerical models used in this thesis research have proved to be efficient enough to recreate the missile's attitude. There are some areas left to explore for further research.

Unstable output of roll sensor could cause cascade effects in the demodulation process. Further investigation is needed to minimize the error of sensed roll angle. A Phase Lock Loop may be reconsidered to recreate the missile's roll in future investigations.

More tests are needed. It will take at least 9 runs for every unit to have enough data for analyzing the various effects. Single axis excitation combined with different excitation rates along with both pitch and yaw excitations will help to determine the cross coupling effects caused by pitch and yaw sensors.

Further research on the alignment of the rate sensors and the roll sensors is required. Research should develop ways to check if the sensors were perfectly orthogonal to each other prior to testing.

By visual checking the position of roll sensor mounted in IMU, it was noted that the Honeywell HMC1002 roll sensor was not mounted in the X-axis. It was mounted 0.65 inch off the central axis and was 58 degrees off the yaw axis. This might cause the roll sensor to produce incorrect roll angle signal. It is recommended that tests be performed with the roll sensor position central to the X-axis to minimize the off-center error for the further research.

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